

Effect of superfluidity on neutron star crustal oscillations

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ABSTRACT

We consider how superfluidity of dripped neutrons in the crust of a neutron star affects the frequencies of the crust's fundamental torsional oscillations. A nonnegligible superfluid part of dripped neutrons, which do not comove with nuclei, act to reduce the enthalpy density and thus enhance the oscillation frequencies. By assuming that the quasi-periodic oscillations observed in giant flares of soft gamma repeaters arise from the fundamental torsional oscillations and that the mass and radius of the neutron star is in the range of $1.4 \leq M/M_\odot \leq 1.8$ and $10 \text{ km} \leq R \leq 14 \text{ km}$, we constrain the density derivative of the symmetry energy as $100 \text{ MeV} \lesssim L \lesssim 130 \text{ MeV}$, which is far severer than the previous one, $L \gtrsim 50 \text{ MeV}$, derived by ignoring the superfluidity.

Key words: relativity – stars: neutron – stars: oscillations – equation of state

The structure of neutron stars remains uncertain mainly because theoretical extrapolations from empirically known properties of atomic nuclei are required to describe the equation of state (EOS) of high density matter inside the star. Consequently, the theoretical neutron star mass (M) - radius (R) relation is still model dependent, whereas the presence of a neutron star that has mass of about $2M_\odot$ has recently been confirmed (Demorest et al. 2010) and plays a role in ruling out some EOS models. It is generally accepted that under an ionic ocean near the star's surface and above a fluid core, there exists a crustal region, where nuclei form a bcc Coulomb lattice in a roughly uniform electron sea and at a density of about $4 \times 10^{11} \text{ g cm}^{-3}$, neutrons drip out of the nuclei. The resultant neutron gas is a superfluid, as long as the temperature is below the critical temperature, and presumably relevant to pulsar glitches (Sauls 1989). In fact, most neutron stars observed are expected to be cool enough to have a crust containing a neutron superfluid. Even at zero temperature, however, a part of the neutron gas comoves non-dissipatively with protons in the nuclei via Bragg scattering off the lattice (Chamel 2012). Crustal torsional oscillations, if occurring in stars, would be controlled by the enthalpy density of the constituents that comove with the protons (van Horn & Epstein 1990). In this article, we thus address how neutron superfluidity affects the oscillation frequencies in a manner that depends on the still uncertain EOS of neutron-rich nuclear matter. We remark that there are earlier publica-

tions that examine the influence of neutron superfluidity on the crustal torsional oscillations for a specific model of the crust EOS (Andersson, Glampedakis, & Samuelsson 2009; Samuelsson & Andersson 2009; Passamonti & Andersson 2012). As we shall see, the effects of neutron superfluidity as analyzed here are consistent with the results obtained in these publications.

It is not long ago that oscillations of neutron stars were observed in the form of quasi-periodic oscillations (QPOs) in giant flares from soft gamma repeaters (SGRs), which are considered to be magnetars, i.e., neutron stars with surface magnetic fields of order 10^{14-15} G . This causes neutron star asteroseismology to become of practical significance in studying the properties of matter in the star (e.g., Andersson & Kokkotas (1996); Sotani, Tominaga, & Maeda (2001); Sotani, Kohri, & Harada (2004); Sotani et al. (2011)). So far, three giant flares have been detected from SGR 0526-66, SGR 1900+14, and SGR 1806-20. The frequencies of the QPOs discovered through the timing analysis of the afterglow are in the range from tens Hz up to a few kHz (Watts & Strohmayer 2006). Many theoretical attempts to explain the observed QPO frequencies have been done in terms of the torsional oscillations in the crustal region and/or the magnetic oscillations (e.g., Levin (2006); Lee (2007); Samuelsson & Andersson (2007); Sotani, Kokkotas, & Stergioulas (2007, 2008); Sotani, Colaiuda, & Kokkotas (2008); Sotani & Kokkotas (2009)). The important conclusion is that either the torsional oscillations or magnetic oscillations dominate the excited oscillations in magnetized neutron stars, depending on the magnetic field strength (Colaiuda & Kokkotas 2011;

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Gabler et al. 2011, 2012a) and configurations (Gabler et al. 2012b). In the absence of the observational information about the magnetic structure of magnetars except the inferred field strengths from the observed spindown (Kouveliotou et al. 1998; Hurley et al. 1999), we assume for simplicity that the QPOs observed in giant flares are associated with the crustal oscillations. Under this assumption, one can probe the properties of nuclear matter in the crust such as the density dependence of the symmetry energy and neutron superfluidity (Steiner & Watts 2009; Sotani 2011; Gearheart et al. 2011; Sotani et al. 2012). Once the density dependence of the symmetry energy is determined, one can address how large the region in which pasta nuclei (rods, slabs, etc.) (Lorenz et al. 1993; Oyamatsu 1993) occur would be, if any (Oyamatsu & Iida 2007).

To quantify the density dependence of the symmetry energy, we use the expansion of the bulk energy per nucleon near the saturation point of symmetric matter at zero temperature (Lattimer 1981):

$$w = w_0 + \frac{K_0}{18n_0^2}(n - n_0)^2 + \left[S_0 + \frac{L}{3n_0}(n - n_0) \right] \alpha^2, \quad (1)$$

where n is the nucleon density, α is the neutron excess, w_0 , n_0 , and K_0 denote the saturation energy, saturation density, and incompressibility of symmetric nuclear matter, respectively, and S_0 and L are the parameters characterizing the symmetry energy coefficient $S(n)$, i.e., $S_0 \equiv S(n_0)$ and $L = 3n_0(dS/dn)_{n=n_0}$. The parameters w_0 , n_0 , and S_0 can be well determined from the empirical masses and radii of stable nuclei (Oyamatsu & Iida 2003), while the parameters L and K_0 are relatively uncertain. In fact, two of us (K.O. & K.I.) constructed the model for the EOS of nuclear matter in such a way as to reproduce Eq. (1) in the limit of $n \rightarrow n_0$ and $\alpha \rightarrow 0$. Then, the optimal density distribution of stable nuclei was obtained from the EOS model within a simplified version of the extended Thomas-Fermi theory. Finally, for given $y(\equiv -K_0 S_0 / 3n_0 L)$ and K_0 , the values of w_0 , n_0 , and S_0 were obtained by fitting the charge number, mass excess, and charge radius calculated from the optimal density distribution to the empirical ones.

To describe matter in the crust, the Thomas-Fermi model was generalized by adding dripped neutrons, a neutralizing background of electrons, and the lattice energy within a Wigner-Seitz approximation (Oyamatsu & Iida 2007). This allows one to obtain the equilibrium nuclear shape and size as well as the crust EOS for various sets of y and K_0 . Here, as in Oyamatsu & Iida (2007) and Sotani et al. (2012), we adopt the parameter range $0 < L < 160$ MeV, $180 \leq K_0 \leq 360$ MeV, and $y < -200$ MeV fm³, which can reproduce the mass and radius data for stable nuclei and effectively cover even extreme cases (Oyamatsu & Iida 2003) (see Table I in Sotani et al. (2012) for the adopted EOS parameters).

We turn to calculations of the eigenfrequencies of the crustal torsional oscillations. We first prepare the equilibrium configuration of the non-rotating neutron stars, which is the spherically symmetric solution of the Tolman-Oppenheimer-Volkoff (TOV) equations. The corresponding solution is described in the following metric with the spherical polar coordinate:

$$ds^2 = -e^{2\Phi(r)} dt^2 + e^{2\Lambda(r)} dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2). \quad (2)$$

In constructing a neutron star from its center, one needs the EOS for matter in the core as well as the crust EOS. Although the core EOS dominates M and R , even the constituents of the core remain uncertain. We thus concentrate on the crustal region without specifying the core EOS. In doing so, for various sets of M and R and various models for the crust EOS, we integrate the TOV equations inward from the star's surface, as in Iida & Sato (1997) and Sotani et al. (2012). Hereafter, we shall consider typical values of M and R , namely, $1.4 \leq M/M_\odot \leq 1.8$ and $10 \text{ km} \leq R \leq 14 \text{ km}$. Note that such choice of M and R , which is rather arbitrary, encapsulates uncertainties of the core EOS.

In the presence of torsional oscillations, the elasticity of the crust works as a restoring force. This elasticity is characterized by the shear modulus μ , which is another ingredient of the calculations of the oscillation frequencies. By assuming that spherical nuclei with charge Ze form a bcc Coulomb crystal with number density n_i , one can approximately describe the shear modulus averaged over all directions in the limit of zero temperature as $\mu = 0.1194n_i(Ze)^2/a$, where $a \equiv (3/4\pi n_i)^{1/3}$ is the Wigner-Seitz radius (Ogata & Ichimaru 1990; Strohmayer et al. 1991). As shown in Sotani et al. (2012), this modulus, which depends on L mainly through the L dependence of Z (Oyamatsu & Iida 2007), controls the L dependence of the oscillation frequencies. Note that pasta nuclei, if present, would contribute to the restoring force in a manner that depends on the shapes (Pethick & Potekhin 1998). However, the values of L that will be constrained from the present analysis suggest that the region where pasta nuclei occur is highly limited (Oyamatsu & Iida 2007). Thus, as in Gearheart et al. (2011) and Sotani et al. (2012), we simply consider the torsional oscillations to be confined within the region of spherical nuclei.

Calculations of the frequencies of the torsional modes on the spherical equilibrium configuration of the crust as obtained above can be performed with high accuracy by using the relativistic Cowling approximation, namely, neglecting the metric perturbations. This is due to the incompressibility of the modes. With the ϕ -component of the Lagrangian displacement vector of a matter element given by $\xi^\phi = \mathcal{Y}(t, r)\partial_\theta P_\ell / \sin\theta$, where P_ℓ is the ℓ -th order Legendre polynomial, the perturbation equation governing the torsional oscillations can be derived from the linearized equation of motion as (Schumaker & Thorne 1983)

$$\begin{aligned} \mu r^2 \mathcal{Y}'' &+ [(4 + r\Phi' - r\Lambda')\mu r + \mu' r^2]\mathcal{Y}' \\ &+ [r^2 H \omega^2 e^{-2\Phi} - (\ell + 2)(\ell - 1)\mu]e^{2\Lambda}\mathcal{Y} = 0. \end{aligned} \quad (3)$$

Here, we assume $\mathcal{Y} = e^{i\omega t}\mathcal{Y}(r)$, the prime denotes the derivative with respect to r , and H is the enthalpy density defined as $H \equiv \epsilon + p$ with the pressure p and the energy density ϵ . We remark that at zero temperature, the baryon chemical potential μ_b can be expressed as $\mu_b = H/n_b$ with the baryon density n_b . The boundary conditions to be imposed in determining the frequency ω of the modes are the zero-traction condition at the density where spherical nuclei ceases to be present in the deepest region of the crust and the zero-torque condition at the star's surface (Schumaker & Thorne 1983; Sotani, Kokkotas, & Stergioulas 2007).

We now consider the effect of neutron superfluidity. It is generally accepted that at a density of about $4 \times 10^{11} \text{ g cm}^{-3}$, neutrons start to be dripped out of nuclei and form

a superfluid. Even at zero temperature, however, a component that undergoes Bragg scattering from the bcc lattice of the nuclei and thus move non-dissipatively with the nuclei is still present. According to recent band calculations beyond the Wigner-Seitz approximation by Chamel (2012), the superfluid density, which we define as the density of neutrons that are not locked to the motion of protons in the nuclei, depends sensitively on the baryon density above neutron drip. Since the crustal torsional oscillations are transverse, only neutrons that are responsible for the superfluid density behave independently of the associated displacements of the nuclei (Pethick, Chamel, & Reddy 2010). However, the enthalpy density H in Eq. (3) fully contains the superfluid mass density (Iida & Baym 2002). We thus subtract the superfluid mass density from H and obtain the effective enthalpy density $\tilde{H} = H \times (A - N_s)/A$, where A denotes the total nucleon number in a Wigner-Seitz cell, and N_s denotes the number of neutrons in a Wigner-Seitz cell that do not comove with the nucleus. Finally, by substituting \tilde{H} for H in Eq. (3), one can determine the frequencies of the torsional oscillations in a manner that depends on N_s . Hereafter we will assume that N_s comes entirely from the gas of dripped neutrons. In fact, although it could come partially from neutrons inside a nucleus, the dripped neutron gas dominates A in the entire density region except just above neutron drip.

We show the results for the frequency of the fundamental $\ell = 2$ torsional oscillations, ${}_0t_2$, calculated for various values of N_s/N_d with the number N_d of dripped neutrons in a Wigner-Seitz cell. We remark that $N_d - N_s$ corresponds to the number of dripped neutrons bound to the nuclei. First, for simplicity, we set the ratio N_s/N_d constant throughout the density region above neutron drip. At given M , R , and N_s/N_d , we calculate ${}_0t_2$ for nine sets of the EOS parameters, as in Sotani et al. (2012). Since the calculated ${}_0t_2$ has a negligible dependence on K_0 , we construct a fitting formula as ${}_0t_2 = c_0 - c_1 L + c_2 L^2$, where c_0 , c_1 , and c_2 are positive and adjusted in such a way as to well reproduce the calculations for the nine cases. The formulas obtained for $N_s/N_d = 0, 0.2, 0.4, 0.6, 0.8, 1$, $M = 1.8M_\odot$, and $R = 14$ km are plotted in Fig. 1. From this figure, one can observe that, due to neutron superfluidity, which acts to enhance the shear speed defined as $v_s = (\mu/\tilde{H})^{1/2}$, ${}_0t_2$ becomes up to 66–82% larger for $L \leq 76.4$ MeV and up to 131% larger for $L = 146.1$ MeV than that without neutron superfluidity. Additionally, in this figure we plot the result for the stellar model with the values of N_s/N_d derived from band calculations in Chamel (2012) as “ n_n^c/n_n^f ” in Table I. Since these values are only of order 10–30% at $n_b \sim 0.01\text{--}0.4n_0$, the increase in ${}_0t_2$ is relatively small and close to the result obtained at $N_s/N_d = 0.2$. Such increase in ${}_0t_2$ is consistent with the results of Andersson, Glampedakis, & Samuelsson (2009); Samuelsson & Andersson (2009); Passamonti & Andersson (2012).

This increase of ${}_0t_2$ due to neutron superfluidity would make the constraint of L severer if the QPO frequencies observed in SGRs come from the torsional oscillations. In this case, the lowest frequency in the observed QPOs should be equal to or larger than the predicted ${}_0t_2$, because ${}_0t_2$ is the lowest frequency among various eigenfrequencies of the torsional oscillations. It is also important to note the tendency that, as M and R become larger, ${}_0t_2$ becomes smaller (Sotani et al. 2012). Consequently, ${}_0t_2$ obtained for

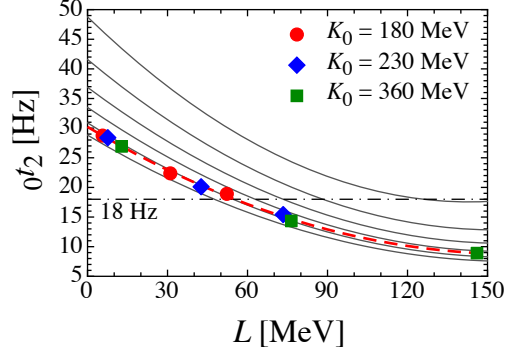


Figure 1. (Color online) Frequencies of the $\ell = 2$ fundamental torsional oscillations of a star having $M = 1.8M_\odot$ and $R = 14$ km, ${}_0t_2$, plotted as a function of L . The six solid lines from bottom to top correspond to the cases of $N_s/N_d = 0, 0.2, 0.4, 0.6, 0.8$, and 1, while the broken line with symbols shows the result from the values of N_s/N_d derived by Chamel (2012). The horizontal dot-dashed line denotes the lowest QPO frequency observed from SGR 1806-20.

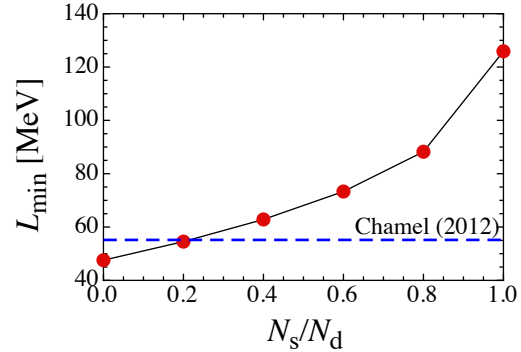


Figure 2. (Color online) L_{\min} as a function of N_s/N_d . The horizontal broken line corresponds to the result from the band calculations of N_s/N_d by Chamel.

$M = 1.8M_\odot$ and $R = 14$ km would determine the lower limit of the allowed L from the observed QPO frequencies, as long as we confine the stellar models within $1.4 \leq M/M_\odot \leq 1.8$ and $10 \text{ km} \leq R \leq 14 \text{ km}$.

This lower limit of L , hereafter referred to as L_{\min} , can be obtained from the intersections between the horizontal dot-dashed line of 18 Hz and the lines of ${}_0t_2$ in Fig. 1. For constant N_s/N_d , the resultant L_{\min} is shown in Fig. 2. One can observe that the value of L_{\min} , which is 47.6 MeV in the absence of neutron superfluidity (i.e., $N_s/N_d = 0$), can be as large as 125.9 MeV in its presence (i.e., $0 < N_s/N_d \leq 1$). In addition, we exhibit $L_{\min} = 55.2$ MeV, the result from the broken line in Fig. 1. This L_{\min} , which comes from the realistic band calculations of N_s/N_d in Chamel (2012), is expected to give a reliable constraint on L .

Instead of just considering L_{\min} , we now proceed to obtain a more stringent constraint on L by fitting the predicted frequencies of fundamental torsional oscillations with different values of ℓ to the low-lying QPO frequencies observed in SGRs. To this end, we use the values of N_s/N_d derived by Chamel (2012). In the present analy-

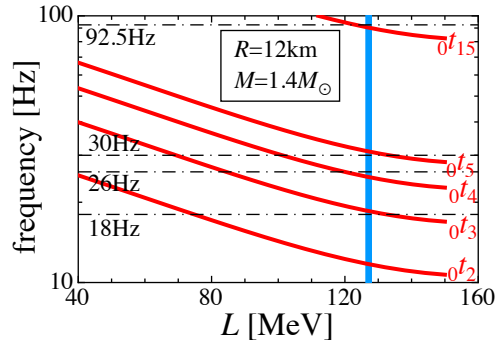


Figure 3. (Color online) Comparison of the calculated frequencies of torsional oscillations of a star having $M = 1.4M_\odot$ and $R = 12$ km (solid lines) with the QPO frequencies observed in SGR 1806-20 (dot-dashed lines), where we adopt the Chamel data for N_s/N_d . The vertical line corresponds to the value of L that is consistent with the observations.

sis, we focus on the observed QPO frequencies lower than 100 Hz, i.e., 18, 26, 30, and 92.5 Hz in SGR 1806-20 and 28, 54, and 84 Hz in SGR 1900+14 (Watts & Strohmayer 2006). In fact, the even higher observed frequencies would be easier to explain in terms of multipolar fundamental and overtone frequencies \dagger . Because of the small interval between the observed frequencies 26 and 30 Hz in SGR 1806-20, it is more difficult to explain the QPO frequencies observed in SGR 1806-20 than those in SGR 1900+14 (Sotani, Kokkotas, & Stergioulas 2007). If one identifies the lowest frequency in SGR 1806-20 (18 Hz) as the fundamental torsional oscillation with $\ell = 3$ as in Sotani (2011), one can manage to explain 26, 30, and 92.5 Hz in terms of those with $\ell = 4, 5$, and 15. In the case of the typical neutron star model with $M = 1.4M_\odot$ and $R = 12$ km, we compare the predicted frequencies with the observed ones as shown in Fig. 3. One can observe from this figure that the best value of L to reproduce the observed frequencies is $L = 127.1$ MeV, where the calculated frequencies, 18.5 Hz ($\ell = 3$), 24.9 Hz ($\ell = 4$), 31.0 Hz ($\ell = 5$), and 90.3 Hz ($\ell = 15$), are within less than 5% deviations from the observations.

Let us now extend the analysis to different stellar models and to SGR 1900+14. We find that the QPOs observed in SGR 1806-20 can be explained in terms of the eigenfrequencies of the same ℓ within similar deviations even for different stellar models except for the case with $M = 1.4M_\odot$ and $R = 10$ km. The obtained best values of L to explain the observations are shown in Fig. 4 by solid lines and filled symbols. On the other hand, the low-lying QPOs observed in SGR 1900+14 can be similarly explained in terms of the fundamental torsional oscillations with $\ell = 4, 8$, and 13; the obtained best values of L are shown in Fig. 4 by broken lines and open symbols. As a result, the allowed region of L where the QPO frequencies observed in SGR 1806-20 and in SGR 1900+14 are reproducible simultaneously lies in the range $100 \text{ MeV} \lesssim L \lesssim 130 \text{ MeV}$, as long as the oscillating neutron

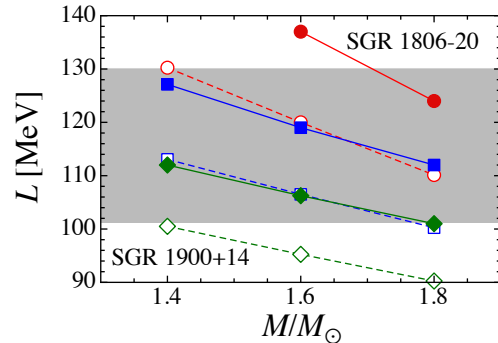


Figure 4. (Color online) Values of L at which the calculated frequencies of torsional oscillations agree best with the QPO frequencies observed in SGR 1806-20 (filled symbols with solid lines) and in SGR 1900+14 (open symbols with broken lines), where the lines are just eye guides. The circles, squares, and diamonds correspond to the stellar models with $R = 10, 12$, and 14 km, respectively. The gray region denotes the allowed values of L that can be obtained from both of the QPO observations in SGR 1806-20 and SGR 1900+14 by assuming that the corresponding neutron stars have mass and radius in the range $1.4 \leq M/M_\odot \leq 1.8$ and $10 \text{ km} \leq R \leq 14 \text{ km}$.

stars have mass and radius ranging $1.4 \leq M/M_\odot \leq 1.8$ and $10 \text{ km} \leq R \leq 14 \text{ km}$. It is interesting to compare this constraint with various experimental constraints on L (See, e.g., Li, Chen, & Ko (2008); Tsang et al. (2009)), which have yet to converge but seemingly favor smaller L . We remark that as in Steiner & Watts (2009), one can also explain the three QPOs observed in SGR 1900+14 in terms of the $\ell = 3, 6, 9$ oscillations with comparable or even better accuracy, but the optimal values of L , which are typically of order 80 MeV, are too low to become consistent with those based on the identification of the four QPOs in SGR 1806-20 as the $\ell = 3, 4, 5, 15$ oscillations.

In summary, we have examined how neutron superfluidity affects the fundamental torsional oscillations in the crustal region of a neutron star for various EOS and stellar models. Recent calculations of the superfluid density allow us to determine the increase in the frequencies of fundamental torsional oscillations, of which the comparison with the QPO frequencies observed in SGRs gives a more stringent constraint on the parameter L characterizing the density dependence of the symmetry energy than the earlier work ignoring the superfluidity (Sotani et al. 2012). If the mass and radius of the oscillating neutron stars are observationally determined, one might be able to justify the assumption that the QPOs come from the torsional modes and then to fix L with reasonable accuracy. We remark that there could be another way of identifying the low-lying QPOs, although the 26 Hz QPO in SGR 1806-20 remains to be clearly identified (Steiner & Watts 2009). In these identifications, the 18, 30, 92.5 Hz QPOs in SGR 1806-20 correspond to the $\ell = 2, 3, 10$ oscillations, while the 28, 54, 84 Hz QPOs in SGR 1900+14 correspond to the $\ell = 3, 6, 9$ oscillations. By assuming again that the masses and radii of the oscillating neutron stars satisfy $1.4 \leq M/M_\odot \leq 1.8$ and $10 \text{ km} \leq R \leq 14 \text{ km}$, we obtain a range of L of $\sim 60 - 80$ MeV in which all the six QPO frequencies are reproducible. It would be interesting to note the difference from the L values of $\sim 100 - 130$

\dagger The possibility to explain the higher QPO frequencies with the shear oscillations in hadron-quark mixed phase in the core of neutron stars is also suggested in Sotani, Maruyama, & Tatsumi (2012).

MeV obtained above and, if the 26 Hz QPO in SGR 1806-20 could be successfully identified as a different type of oscillation from the torsional ones, to consider which of these two allowed ranges of L is more favored.

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